Singlet Assisted Electroweak Phase Transitions and Precision Higgs Studies

Peter Winslow

Based on:

PRD **91**, 035018 (2015) (arXiv:1407.5342)
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arXiv:1510.XXXX
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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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Outline

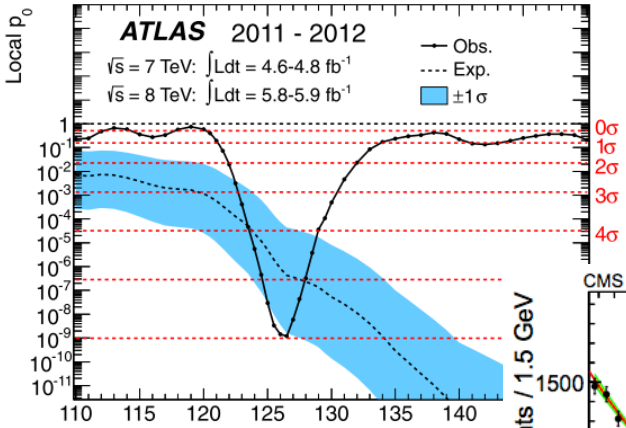
Singlets: Collider Physics $\longleftrightarrow$ Cosmology

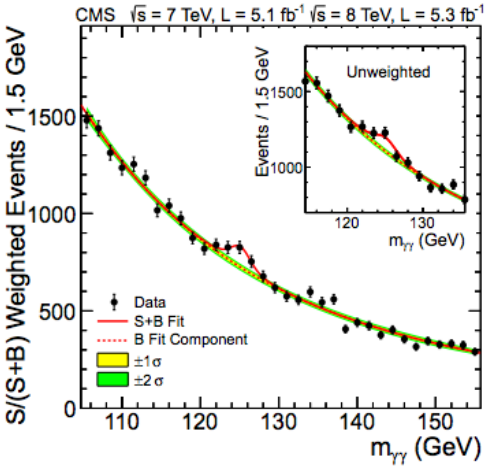
The xSM: a Minimally Extended Scalar Sector

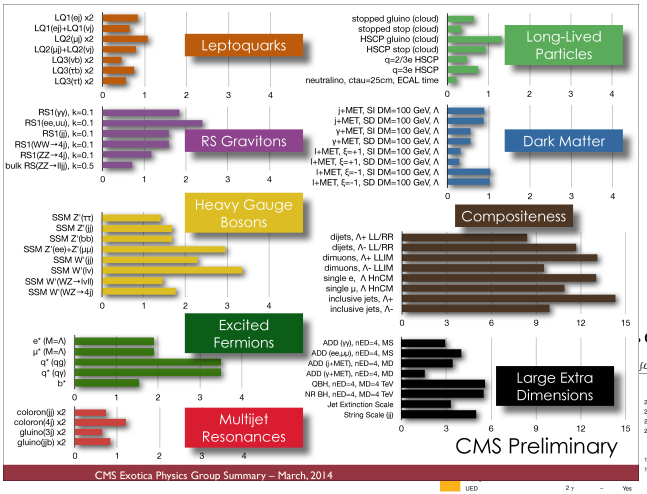
1st Order Phase Transitions: Electroweak Baryogenesis in the xSM

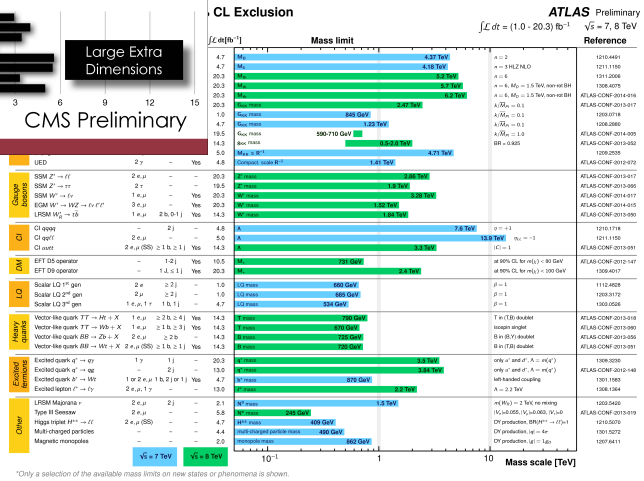
NextGen Colliders: A motivation from Cosmology

LHC has thrown open the door to the scalar sector of the SM!



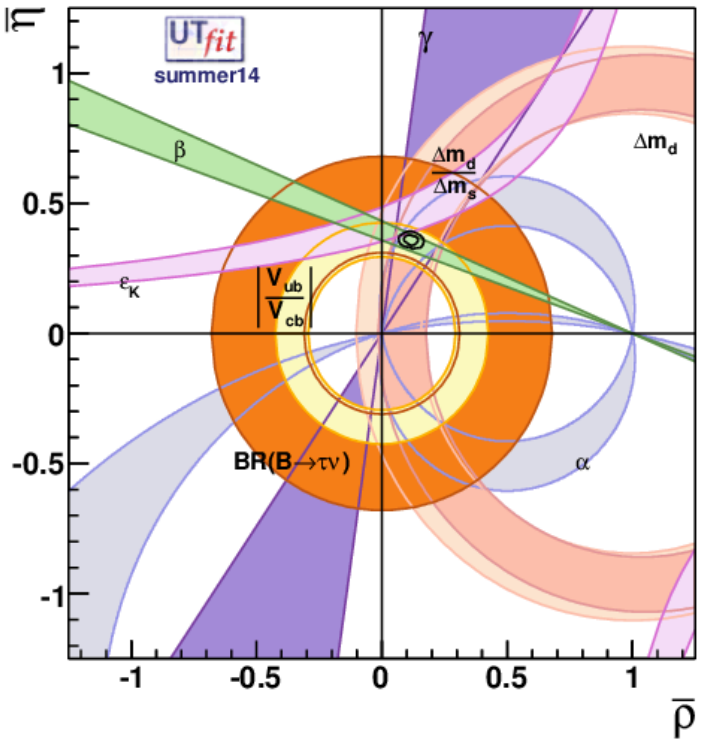


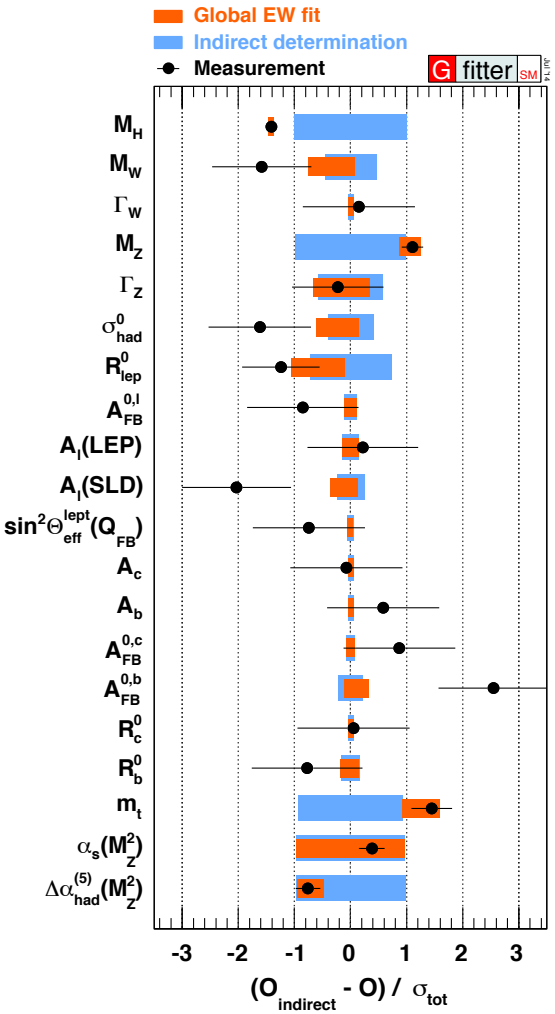




… but where's all the NP?

No obvious hints from CKM-ology or EWPO either…





Options:

→ Heavy NP

→ Weakly coupled NP

→ Clever NP (compressed spectra, etc.)

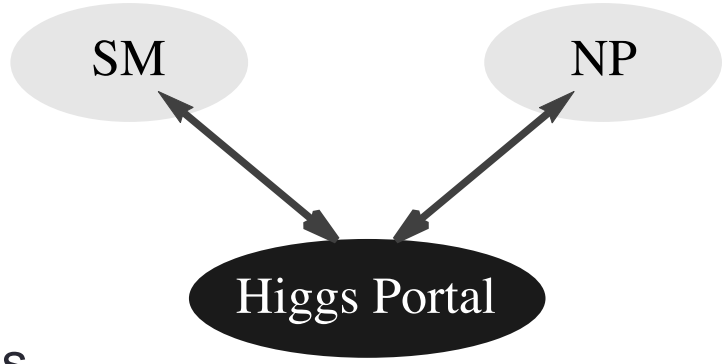
→ **Hidden Sectors / Singlets**

Singlets:

- Less constrained (possibly still weak scale)

- Typically still couple to SM via portals
  → Interesting collider signatures

- Also motivated by real cosmological problems



$$\Delta\mathcal{L} \supset \mathcal{O}_{NP}|H|^2$$

Singlets:

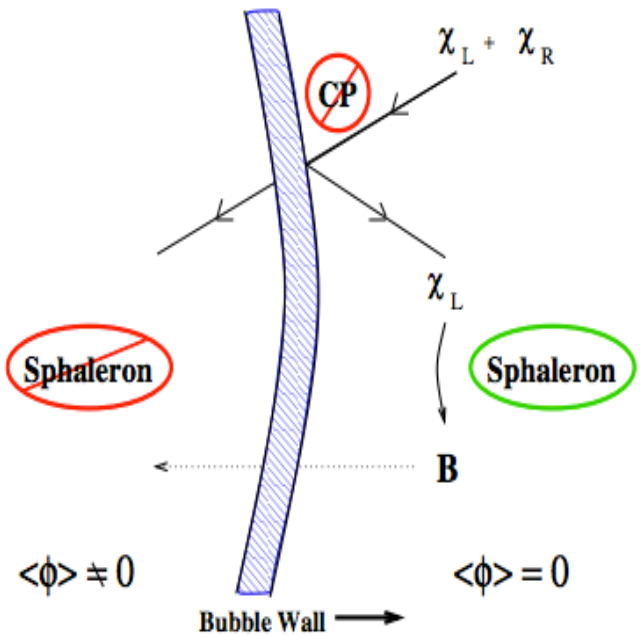
- Less constrained (possibly still weak scale)

- Typically still couple to SM via portals
  → Interesting collider signatures

- Also motivated by real cosmological problems
  → ***Matter/Antimatter Asymmetry***

- Higgs portals can modify character of EWPT
  → Strongly 1st order EWPT
    → Highly motivated by EWBG

Electroweak Baryogenesis



Requirement of a SFOEWPT identifies a preferred parameter space
→ ***Cosmological motivation for collider searches***

The xSM: a useful toy model

$$V_{xSM}(H,S) = V_{SM}(H) + \underbrace{\left(\frac{a_1}{2}S + \frac{a_2}{2}S^2\right)|H|^2}_{Higgs\ Portal} + \overbrace{\frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4}^{Secluded\ Self-Interactions}$$

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v_0 + h + iG^0\right) \end{pmatrix}, \quad S = x_0 + s$$

Higgs Mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\sin 2\theta = \frac{(a_1 + 2a_2x_0)v_0}{(m_1^2 - m_2^2)}$$

- Set m_{h1} = 125 GeV
- h_1 (h_2) couplings to SM rescaled by cosθ (sinθ)
- Singlet inherits SM couplings entirely from mixing
  - → searches for heavy scalars
  - → EW precision observables

Strong 1st order EWPTs in the xSM

Connecting to EWPT requires finite temperature effective potential

$$V_{eff}(\phi, T) = V_0(\phi) + V_{CW}(\phi) + V^{T\neq 0}(\phi, T) + V^{\text{Ring-sum}}(\phi, T)$$

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→ Gauge dependent!! JHEP 1107 (2011) 029

→ Independence restored at high temperature

$$V_{eff}(\phi, \alpha, T)^{xSM} \overset{\text{High T}}{\Longrightarrow} \bar{D}(T^2 - T_0^2)\phi^2 + e\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

$$v(T)/\sqrt{2} = \phi(T)\cos\alpha(T),\ x(T) = \phi(T)\sin\alpha(T)$$

Condition for SFOEWPT

$$\cos\alpha(T_c)\frac{\Delta\phi(T_c)}{T_c} \gtrsim 1$$

$$\Longrightarrow -\cos\alpha(T_c)\frac{e}{2T_c\bar{\lambda}} \gtrsim 1$$

SFOEWPT driven by tree-level parameters

→ Classical transition

$$e = \left(\frac{a_1}{2}\cos^2\alpha + \frac{b_3}{3}\sin^2\alpha\right)\sin\alpha$$

$$\bar{\lambda} = \lambda\cos^4\alpha + \frac{a_2}{2}\cos^2\alpha\sin^2\alpha + \frac{b_4}{4}\sin^4\alpha$$

Strong 1st order EWPTs in the xSM

General requirements for SFOEWPT:

- Large $\cos\alpha(T_c)$

- Large, negative a_1
  → Raises barrier

- $\bar{\lambda}$ linearly related to T_C
  → λ correlated with T_C

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True value is slightly higher in xSM

PRD 90 (2014) 1, 015015

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Phenomenology depends largely on mass

Possible collider signatures

$m_2 < 2\ m_1$ → BSM Higgs-like decay modes

$m_1/2 < m_2 < 2\ m_1$ → Precision measurements

$m_2 > 2\ m_1$ → Resonant di-Higgs(-like) production

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Motivates precision measurements at future colliders

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Possible collider signatures

For this talk

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$m_1/2 < m_2 < 2\ m_1$ → Precision measurements

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Motivates precision measurements at future colliders

In progress…

Also, see Chien-Yi's Talk!

What do we *know* from current LHC?

What can we *learn* from future colliders?

Indirect Searches: Higgs-like coupling measurements

Fit to current data

$$\chi^2(\theta) = \sum_i \left(\frac{\mu_i^{obs} - \cos^2\theta}{\Delta\mu_i^{obs}} \right)^2$$

Sensitivity from projected uncertainties

$$\chi^2(\theta) = \sum_i \left(\frac{1 - \cos^2\theta}{\Delta\mu_i^{proj}} \right)^2$$

LHC:
All 7-8 TeV data available

HL-LHC:
$\sqrt{s}$ = 14 TeV, 3 ab^{-1}

ATL-PHYS-PUB-2013-014, CMS-NOTE-13-002

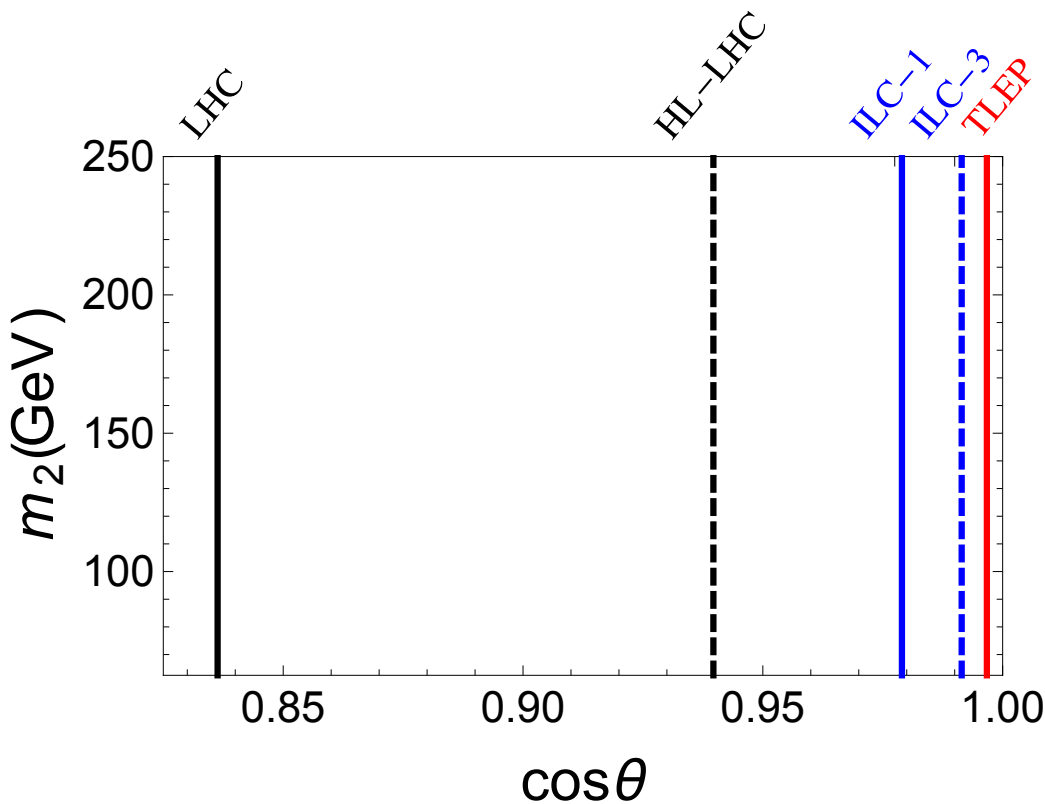
ILC-1:
$\sqrt{s}$ = 250 GeV, 250 fb^{-1}

ILC-3:
$\sqrt{s}$ = 1 TeV, 1 ab^{-1}

ILC Higgs White Paper

TLEP:
$\sqrt{s}$ = 240 GeV, 1 ab^{-1}

arXiv:1305.6498



Indirect Searches: Oblique Parameters

Effects are simple to calculate

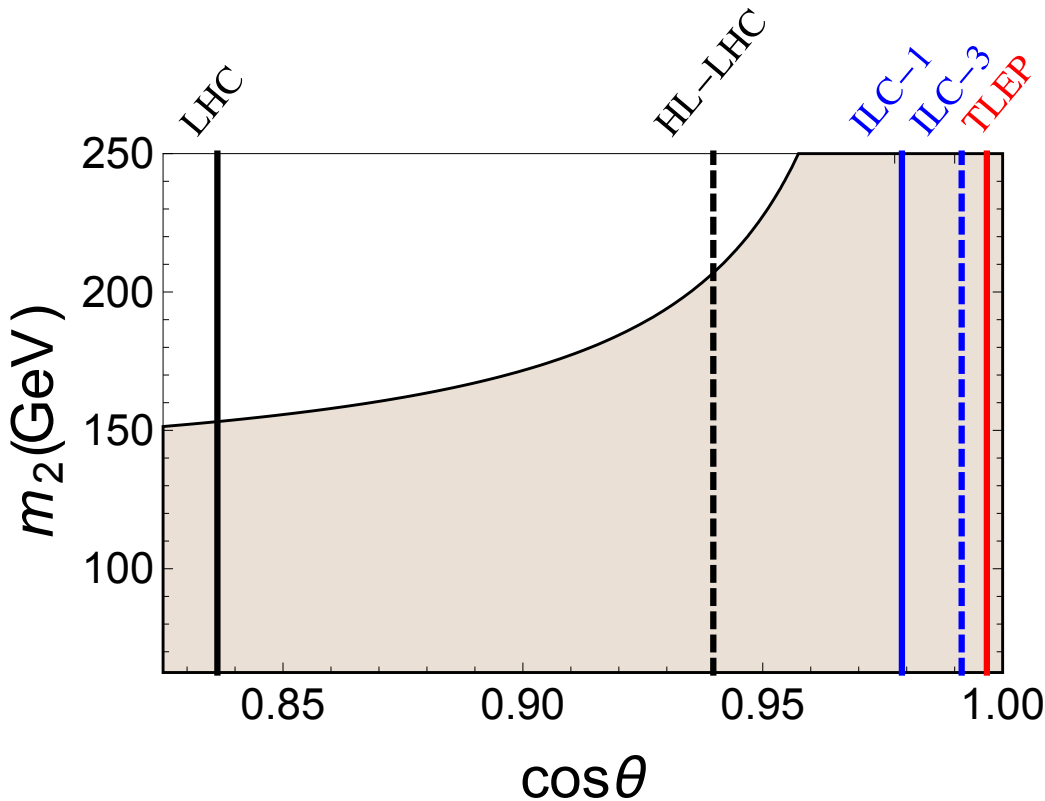
$$\Delta\mathcal{O} = \cos^2\theta\mathcal{O}^{SM}(m_1) + \sin^2\theta\mathcal{O}^{SM}(m_2) - \mathcal{O}^{SM}(m_1)$$
$$= \left(1-\cos^2\theta\right)\left(\mathcal{O}^{SM}(m_2) - \mathcal{O}^{SM}(m_1)\right)$$

$$\mathcal{O} = S, T, U$$

Perform full fit to current best-fit values from Gfitter

$$\Delta\chi^2 = \sum_{i,j}\left(\Delta\mathcal{O}_i - \Delta\mathcal{O}_i^0\right)\left(\sigma^2\right)^{-1}_{ij}\left(\Delta\mathcal{O}_j - \Delta\mathcal{O}_j^0\right)$$

Eur. Phys. J. C **72**, 2205 (2012)



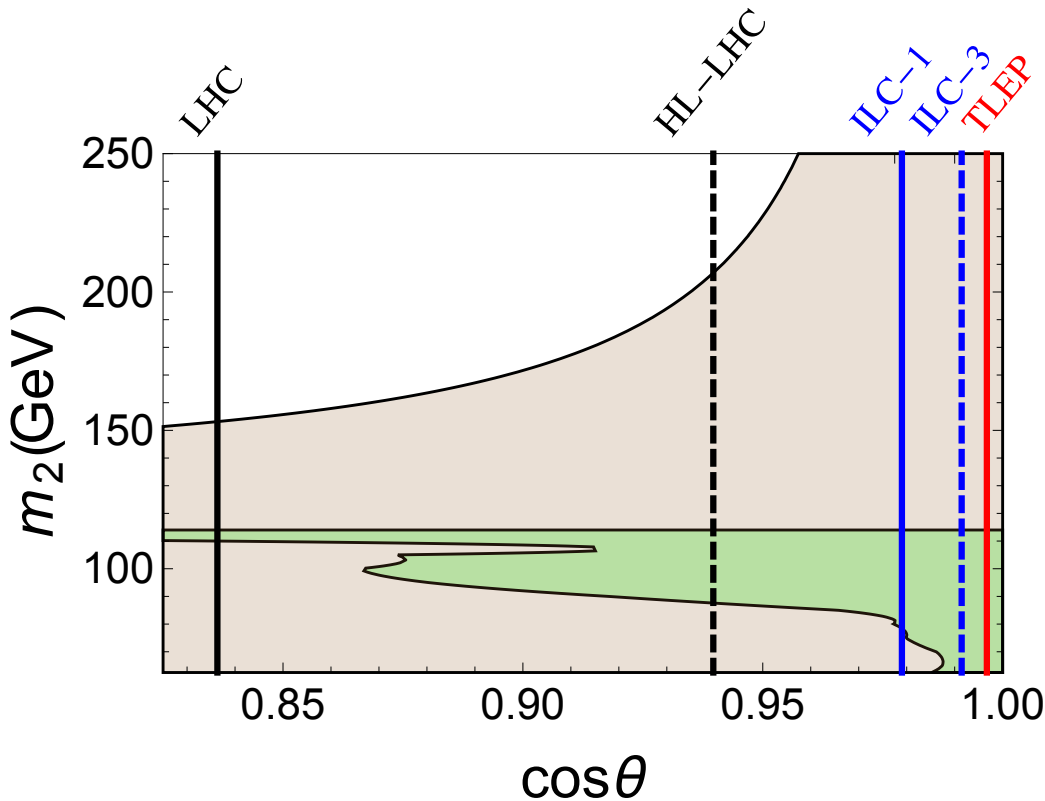
Direct searches: Null results from SM-like Higgs searches

All h_2-SM interactions rescaled by sinθ

$$\mu_{XX} = \frac{\sigma(m_2) \cdot \mathrm{BR}(m_2)}{\sigma^{SM}(m_2) \cdot \mathrm{BR}^{SM}(m_2)} = 1 - \cos^2\theta$$

LEP Searches

Phys. Lett. B **565**, 61 (2003)



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Higgs Discovery

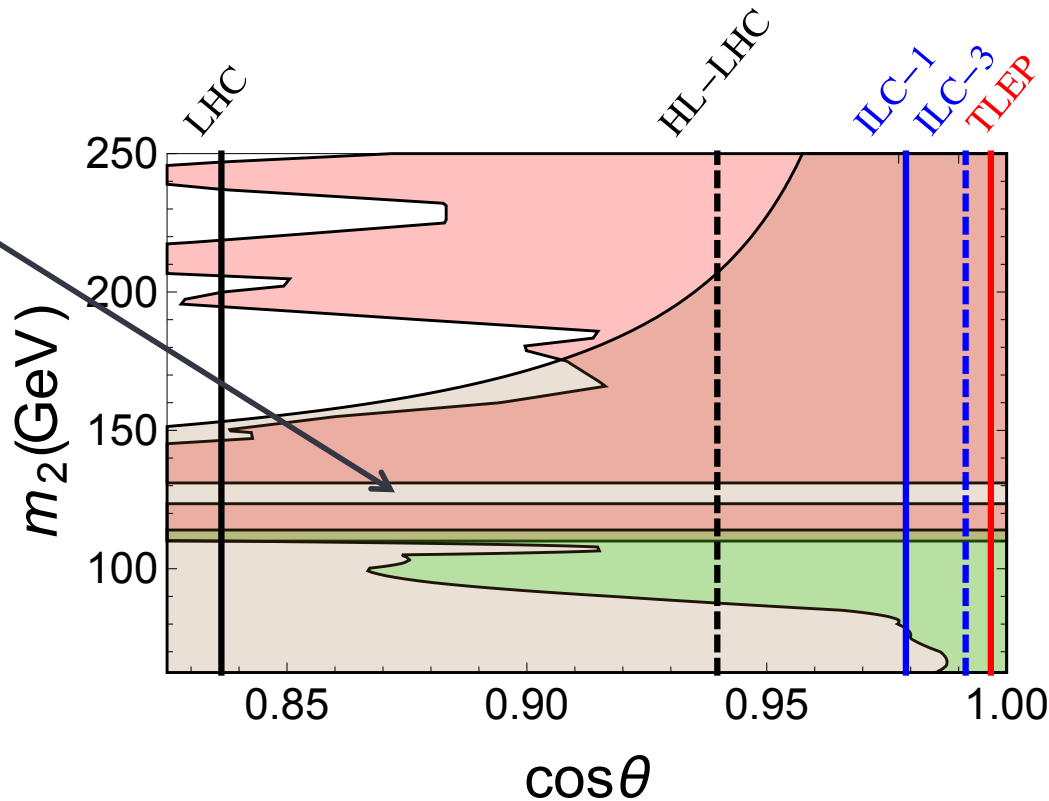
LEP Searches

Phys. Lett. B **565**, 61 (2003)

LHC Searches

→ ATLAS-CMS Combination

Phys. Lett. B **716**, 1 (2012), Phys. Lett. B **716**, 30 (2012)



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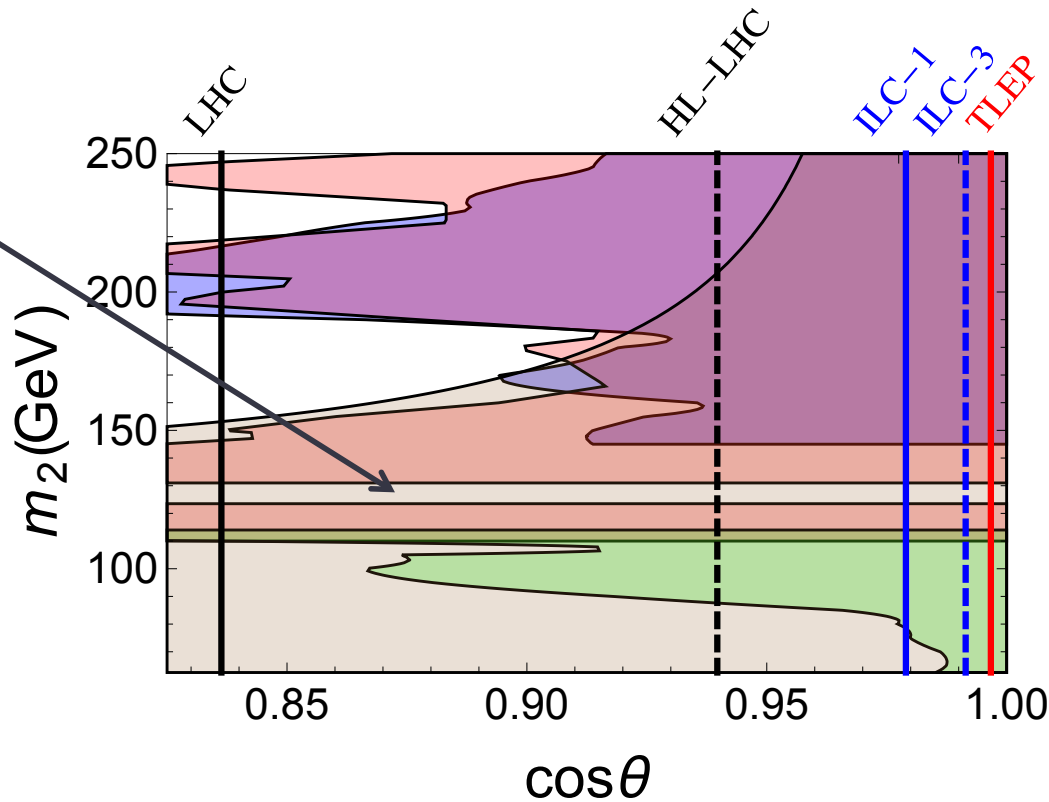
Phys. Lett. B **716**, 1 (2012), Phys. Lett. B **716**, 30 (2012)

Dedicated heavy SM-like Higgs search

→ CMS

Eur. J. Phys. 73, 2469 (2013)



SFOEWPT ⟷ Deviations from SM Higgs tri-linear coupling

Noble, Perelstein
PRD **78** 063518 (2008)

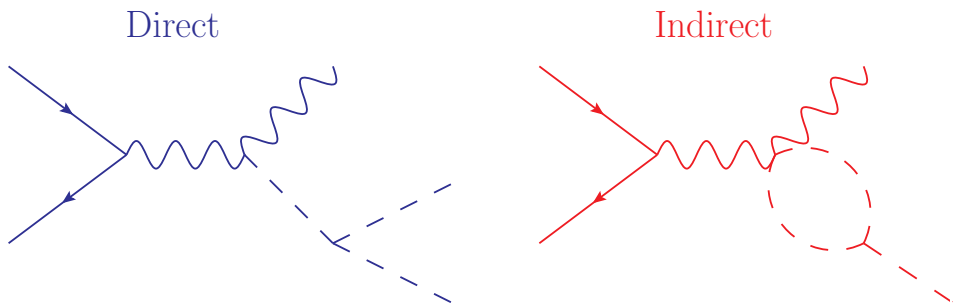
Lepton Colliders

Model-dependent…

$\sqrt{s} > 2\, m_{h_1}$

$\sqrt{s} < 2\, m_{h_1}$

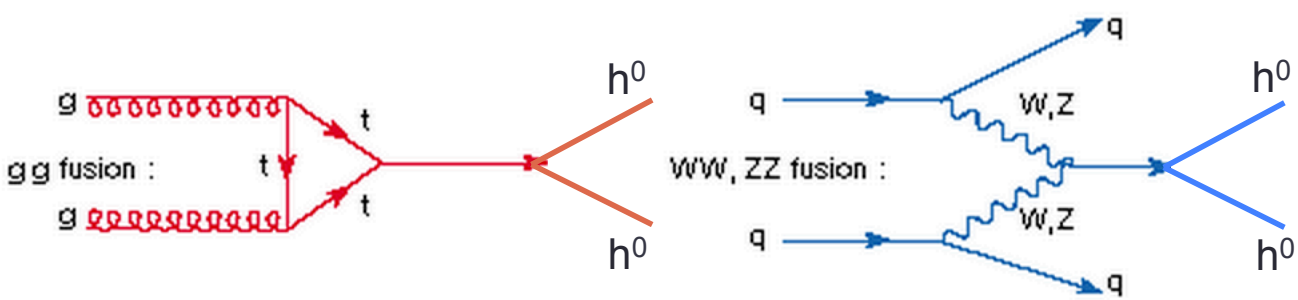
Direct Production



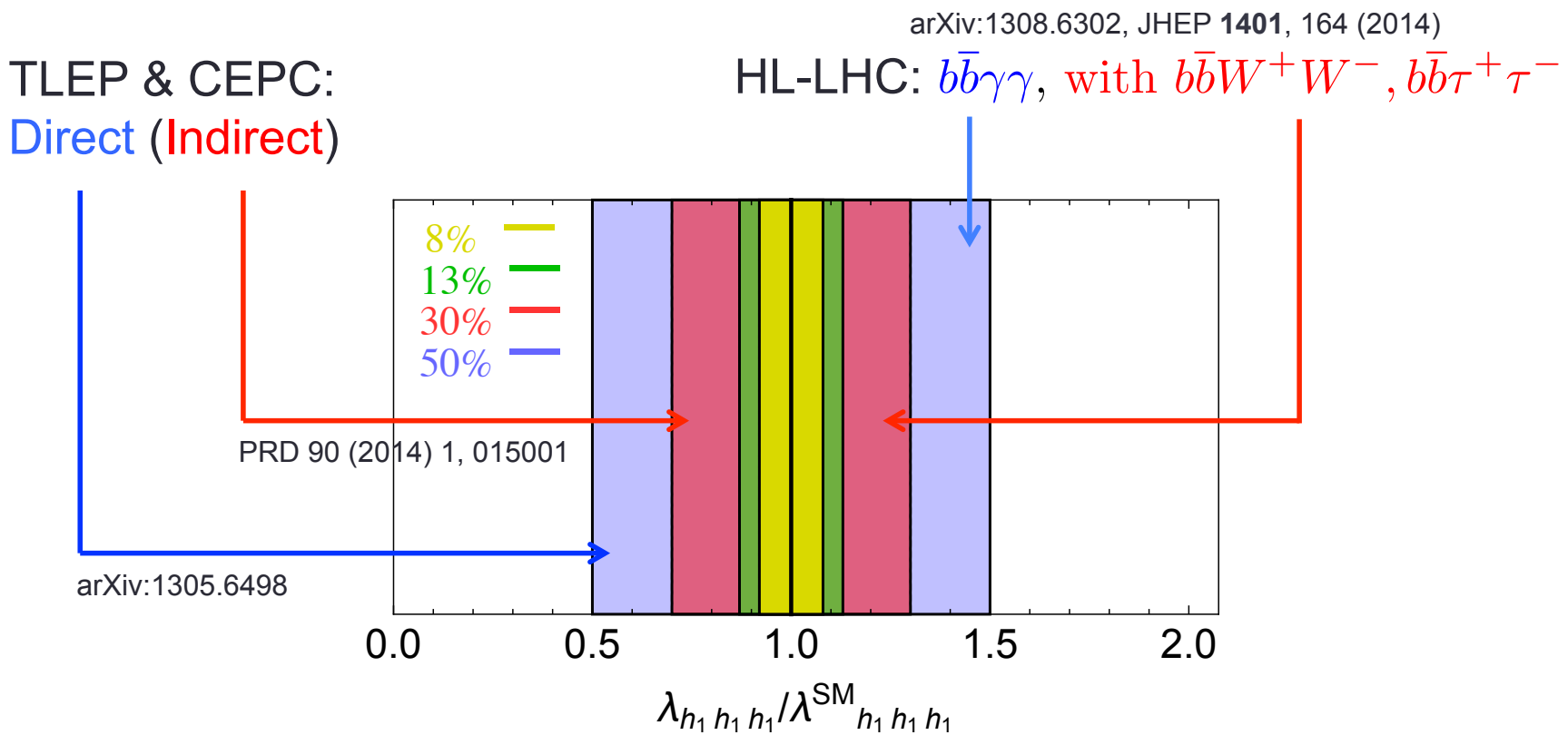
Indirect Production

PRD 90 (2014) 1, 015001

Hadron Colliders



Projected sensitivity to Higgs-like tri-linear self-coupling



Projected sensitivity to Higgs-like tri-linear self-coupling

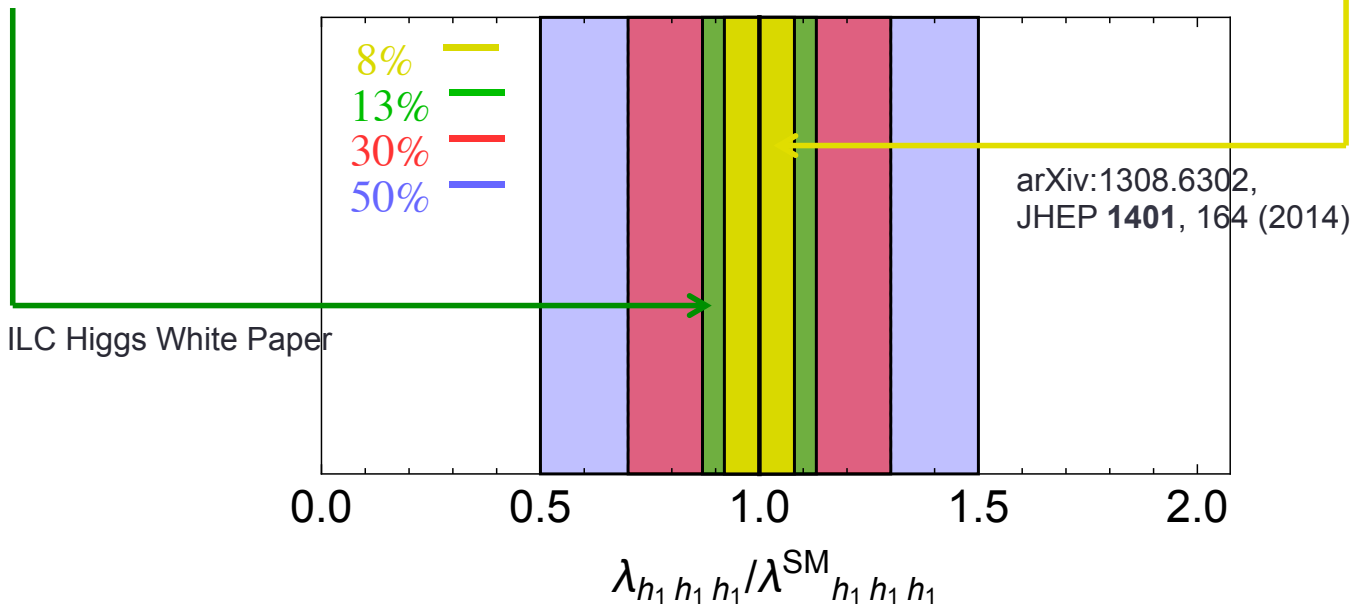
ILC: $e^+e^- \to Zhh$

with $e^+e^- \to \nu\bar{\nu}hh$

VHE-LHC or SPPC
(100 TeV pp collider)

1 TeV
with 2.5/ab

100 TeV
with 3/ab



Projected sensitivity to Higgs-like tri-linear self-coupling

Revised to 100 TeV with 3/ab (30/ab): (~40%) ~10%

JHEP **1502**, 016 (2015)

ILC: $e^+e^- \to Zhh$

with $e^+e^- \to \nu\bar{\nu}hh$

VHE-LHC or SPPC
(100 TeV pp collider)

1 TeV
with 2.5/ab

100 TeV
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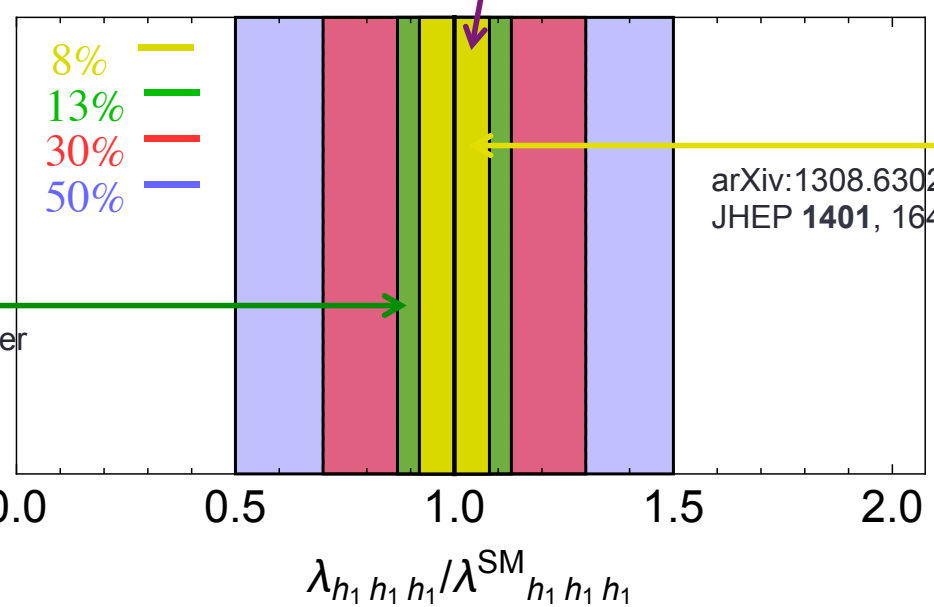


arXiv:1308.6302,
JHEP **1401**, 164 (2014)

ILC Higgs White Paper

Phenomenological Implications

Perform MC scans over xSM space

$$a_1/\mathrm{TeV}, b_3/\mathrm{TeV} \in [-1, 1], \quad x_0/\mathrm{TeV} \in [0, 1], \quad b_4, \lambda \in [0, 1]$$

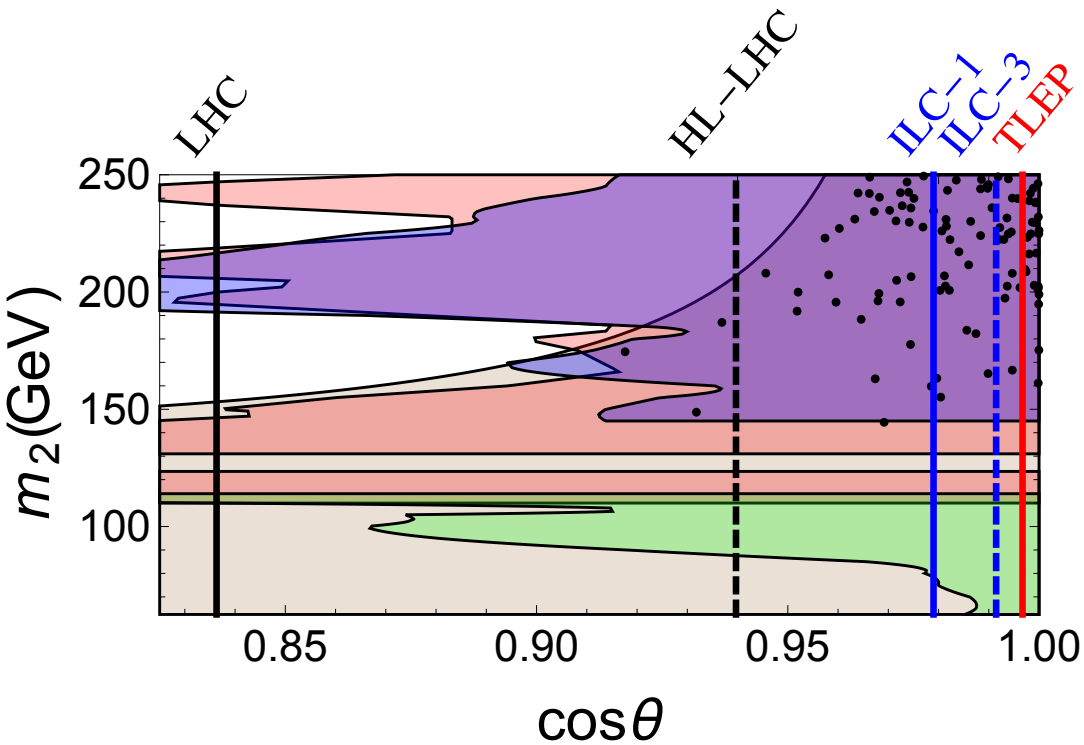
Require: *Current* Collider Constraints | SFOEWPT | Sufficient Tunnelling

CosmoTransitions

SFOEWPT-viable space is biased towards small mixing and large mass splitting.

Motivates:

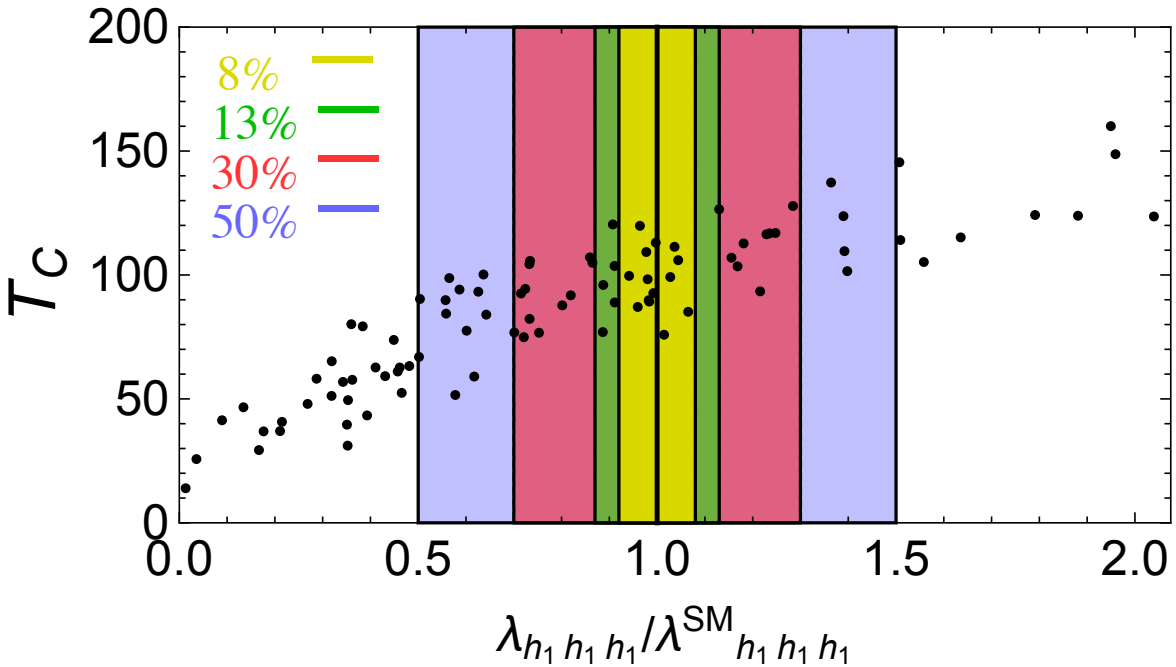
- **High precision Higgs-like coupling measurements**
- **Searches for SM-like Higgs' near di-Higgs threshold**



Phenomenological Implications

Deviations for which $\lambda_{h_1 h_1 h_1} < \lambda^{SM}_{h_1 h_1 h_1}$ correspond to strong quenching of sphalerons!

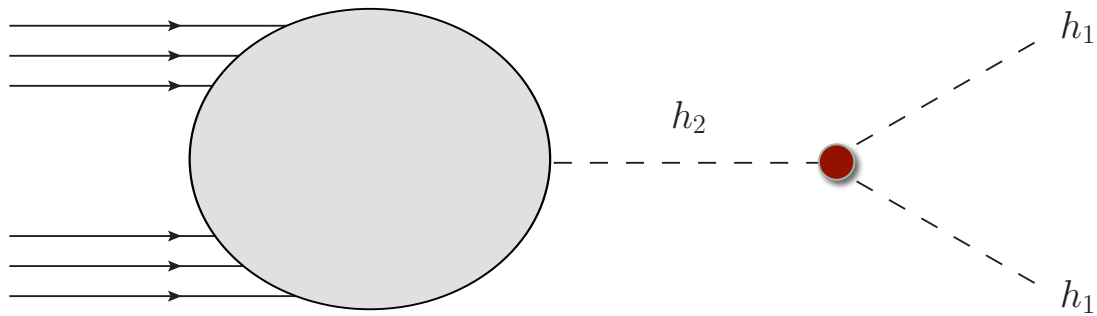
Precision measurements of tri-linear Higgs self-coupling will be powerful probes of SFOEWPT-viable space!



For higher singlet-like masses, $h_2 \rightarrow h_1 h_1$ opens up
→ Resonantly enhanced di-Higgs production becomes possible

What are discovery prospects for models which feature SFOEWPT?

Assume in the resonance region
→ don't account for box graphs



$$\lambda_{211} = \sin\theta \; f(\lambda, x_0, a_1, b_3, b_4)$$

Goal: *Determine benchmark points, based on largest σ BR, which feature a SFOEWPT*
→ ***Concentrate on ggF***

$$\sigma_{LO}(pp(gg) \rightarrow h_2) = \sin^2\theta \; \sigma_0^{ggF} m_2^2 \frac{d\mathcal{L}}{dm_2^2}$$

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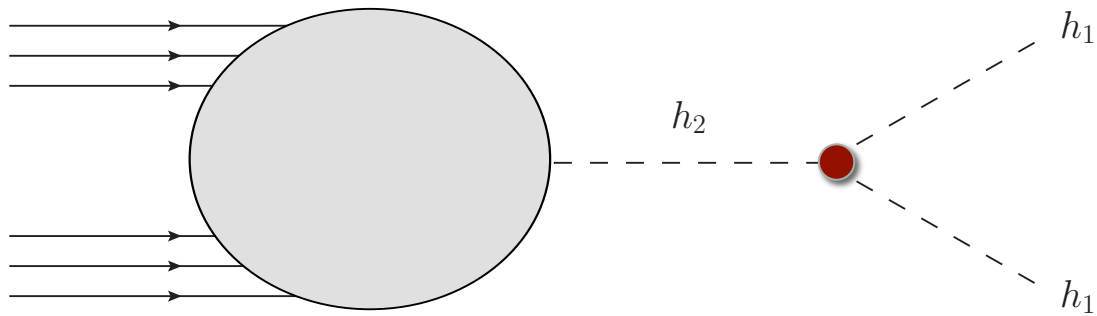

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← Higgs XSWG at 100 TeV

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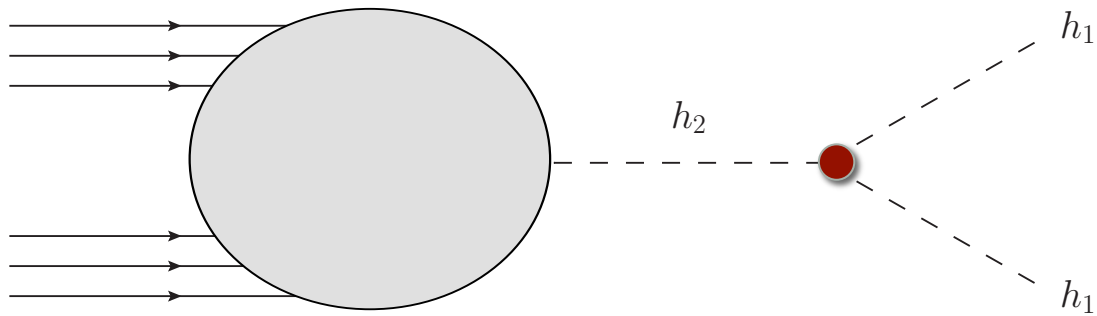

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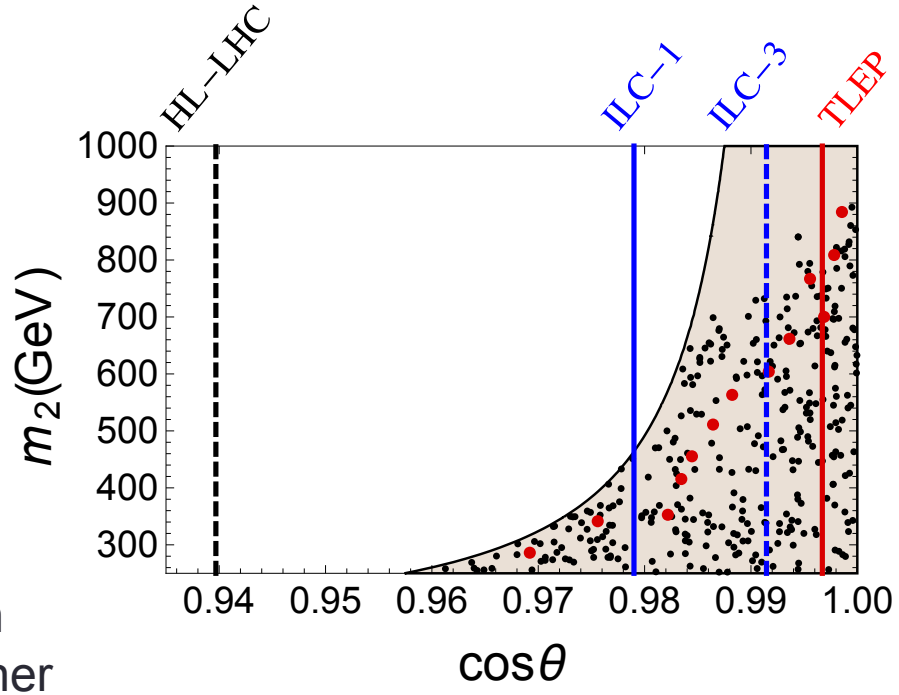
$$BR(h_2 \to h_1 h_1) = \left(1 + \frac{8\pi \sin^2\theta \; m_2 \Gamma^{SM}_{h_1}(m_2)}{\lambda_{211}^2 \sqrt{1 - \frac{4m_1^2}{m_2^2}}}\right)^{-1}$$

Benchmarks	c_θ	m_2 (GeV)	W_{h_2} (GeV)	W_h (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	g_{111}	g_{211}	σ (pb)	BR
B1	0.97	295	0.69	7.89	79	0.17	-437.5	1.87	-166	0.9	45	49	28	0.27
B2	0.95	338.7	4.41	13.31	228	0.94	-484	0.53	-343	0.6	186	-199	52	0.71
B3	0.95	366.9	5.02	19.37	257	0.93	-276	0.01	-380	0.9	184	-206	54.5	0.7
B4	0.96	406.2	3.11	31.21	190	0.66	-952	1.6	-159	0.76	139	-65	51	0.12
B5	0.98	489.3	2.84	63.16	26	0.09	-420	1	-66	0.74	7.1	-43.5	19.5	0.05
B6	0.97	513.6	4.14	74.39	26	0.1	-452	0.3	113	0.65	2	-81.85	19	0.11
B7	0.97	573.9	6.02	106.42	28	[illegible]	[illegible]	1	-222	0.15	6.9	-95.5	14.5	0.1
B8	0.97	614.6	7.29	132.44	[illegible]	0.16	-711	1.5	-962	0.57	9.3	-122	11	0.13
B9	0.97	673.2	11.13	176.72	31	0.23	-944	1.9	-690	0.45	15.5	-137	8.8	0.1
B10	0.98	725.4	8.82	222.26	24	0.16	-844	1.6	-471	0.6	9.7	-133	4.3	0.12
B11	0.99	781.6	4.99	281.85	16	0.1	-632	0.94	952	1	3.6	-105	1.56	0.11
B12	0.98	816.6	10.44	325.53	21	0.16	-909	0.9	315	0.53	5.77	-170	2.3	0.14
B13	0.99	868.4	8.06	398.44	17.4	0.13	-851.2	1.48	711.5	0.26	8	-139	1.13	0.11
B14	0.99	915.3	9.70	475.65	17.6	0.15	-958	1.8	573	0.36	9.6	-154.6	0.93	0.11

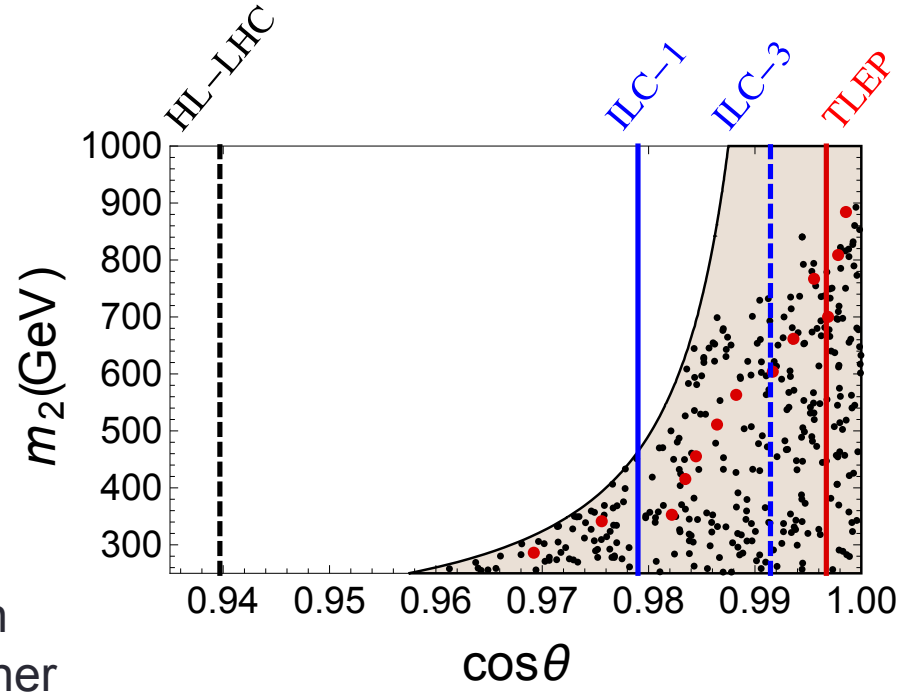
Preliminary



- Simulate events with MG5 + Pythia8
- Choose final states based on BG suppression
  - → bbyy, 4τ, ττyy have smaller σ's but cleaner signatures
    - → 100 TeV collider may yield substantial # of events
- For each final state:
  - Combine distributions
  - Use BDT algorithm to separate signal from BG

Benchmarks	c_θ	m_2 (GeV)	W_{h_2} (GeV)	W_h (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	g_{111}	g_{211}	σ (pb)	BR
B1	0.97	295	0.69	7.89	79	0.17	-437.5	1.87	-166	0.9	45	49	28	0.27
B2	0.95	338.7	4.41	13.31	228	0.94	-484	0.53	-343	0.6	186	-199	52	0.71
B3	0.95	366.9	5.02	19.37	257	0.93	-276	0.01	-380	0.9	184	-206	54.5	0.7
B4	0.96	406.2	3.11	31.21	190	0.66	-952	1.6	-159	0.76	139	-65	51	0.12
B5	0.98	489.3	2.84	63.16	26	0.09	-420	1	-66	0.74	7.1	-43.5	19.5	0.05
B6	0.97	513.6	4.14	74.39	26	0.1	-452	0.3	113	0.65	2	-81.85	19	0.11
B7	0.97	573.9	6.02	106.42	28	[illegible]	[illegible]	1	-222	0.15	6.9	-95.5	14.5	0.1
B8	0.97	614.6	7.29	132.44	[illegible]	0.16	-711	1.5	-962	0.57	9.3	-122	11	0.13
B9	0.97	673.2	11.13	176.72	31	0.23	-944	1.9	-690	0.45	15.5	-137	8.8	0.1
B10	0.98	725.4	8.82	222.26	24	0.16	-844	1.6	-471	0.6	9.7	-133	4.3	0.12
B11	0.99	781.6	4.99	281.85	16	0.1	-632	0.94	952	1	3.6	-105	1.56	0.11
B12	0.98	816.6	10.44	325.53	21	0.16	-909	0.9	315	0.53	5.77	-170	2.3	0.14
B13	0.99	868.4	8.06	398.44	17.4	0.13	-851.2	1.48	711.5	0.26	8	-139	1.13	0.11
B14	0.99	915.3	9.70	475.65	17.6	0.15	-958	1.8	573	0.36	9.6	-154.6	0.93	0.11

Preliminary



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Final results soon!

Conclusions

xSM: a simple framework linking EWPT dynamics to mixing phenomenology, allowing

- EWPT-preferred parameter space to act as a guide for collider searches
- Precision collider measurements to act as a powerful probe of the EWPT

In both cases, SFOEWPT motivates next gen. colliders for the purposes of

- High precision Higgs coupling measurements
- Direct searches for singlet-like scalars

Should future experiments find evidence for

- Non-zero Higgs mixing
- Existence of a singlet-like scalar
- Deviations in $\lambda^{SM}_{h_1 h_1 h_1}$

our work will aid in narrowing down SFOEWPT-viable parameter space

Thank you!

Orange Points: Satisfy Collider Bounds

Black Points: Satisfy EWPT